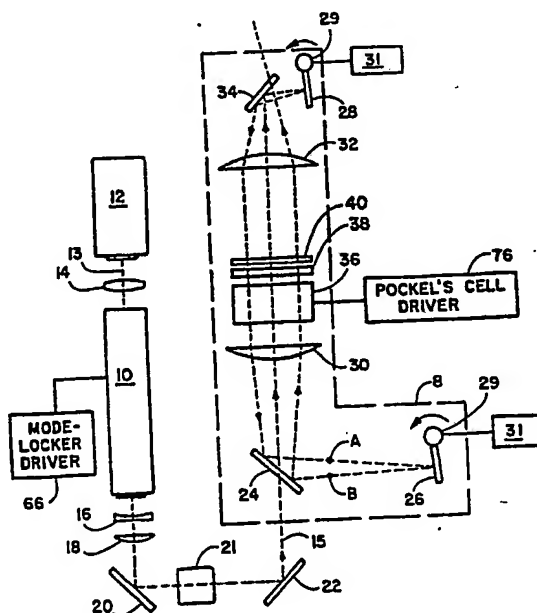




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(54) Title: TWO DIMENSIONAL SCAN AMPLIFIER LASER



## (57) Abstract

The disclosure is directed to a laser amplifier system utilizing a pair of scanning mirrors (28, 44) driven in tandem by piezo actuators (29). A low power laser beam (13) is directed between the pair of scanning mirrors (28, 44). Each bounce of the laser beam (13) between the mirrors (28, 44) discretely increases the power of the beam and changes the angle of exit of the beam from the amplifier providing for precise angular beam exit control.

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## TITLE OF THE INVENTION

Two Dimensional Scan Amplifier Laser

## BACKGROUND OF THE INVENTION

United States patent 3,432,771, Hardy et al., issued March 11, 1969 discloses an apparatus for changing the direction of a light beam in an optical cavity. The cavity consists of a focussing objective, located between two reflectors, such as curved mirrors. The relative position of one center of curvature with the other center of curvature can be controlled by positioning of one of the mirrors. Points on the reflectors are located at the object and the image positions for the objective. When the active medium is suitably excited, the orientation of the lasing mode, and hence the position of the spots of light, is determined by the effective angular positioning of the reflectors.

United States patent 3,480,875, Pole, issued November 25, 1969 disclosed a laser cavity which was set up between a pair of plane mirrors. At least one active laser element is located between the mirrors. A pair of lens systems are positioned between the mirrors so that they have a common focal plane between them. A Kerr cell, polarizers, and a compensator suppress light oscillation along certain reflector paths within the cavity, thereby setting up preferred modes of oscillation along other paths. Laser emission occurs along the preferred paths.

United States patent 3,597,695, James E. Swain, issued

August 3, 1971 disclosed an apparatus for amplifying laser light by multiple passes through a lasing material in a single laser cavity. A single amplifier stage achieved what has been accomplished by several stages. This is accomplished by a switching mechanic which directs a laser beam into and out of the cavity at selected time intervals, thereby enabling amplification of low intensity laser pulses to energy level near the damage limits of the optical components of the system.

United States patent 4,191,928, John L. Emmett, issued March 4, 1980 disclosed a high energy laser system using a regenerative amplifier, which relaxes all constraints on laser components other than the intrinsic damage level of matter, so as to enable use of available laser system components. This can be accomplished by use of segmented components, spatial filter.

"A survey of laser beam deflection techniques," by Fowler and Schlafer, Proceedings of IEEE, vol 54, no. 10, pages 1437-1444, 1966.

The control of laser beam positioning has become a key element in many field of applications such as image processing, graphic display, materials processing, and surgical applications involving precision tissue removal.

Many techniques have been developed for the controlling of the laser beam direction. For the purpose of this invention, this discussion will be limited to the speed, accuracy, and the scan angle range of different devices used in a random access mode.

Galvanometer mirror scanners have a large scan angle range. However, the mechanical response due to the balance of the coil and the applied magnetic field is limited to a few hundred Hertz. The settling time and the oscillation about the equilibrium point further limits the accuracy attainable with such devices.

Mirrors positionable with piezo actuators are capable of accurate hunt free movement response of up to tens of kilo-hertz, depending on the design of the mounts. The typical scan angle is in the order of few milli-radian. Methods to enhance the scan angle has been proposed by J. Schlafer and V. J. Fowler, "A Precision, High Speed, Optical Beam Scanner," Proceedings, International Electron Devices Meeting, 1965. In their report, multiple piezo-mirrors were used to intercept the laser beam, such that the scan angle of the each scanner is contributing to the total of the effect, which is the sum of all scan angles. This device requires many individual scanner units, which multiplies in economic cost with the number of units, and the mirror size also limits the number of units to be used before the beam will miss the last mirror.

Furthermore, both of the above methods are applicable in one dimensional scanning only. For two dimensional scans, an additional unit, which is either and an identical or a mix with another device must be provided for the scanning in the other dimension, doubling the cost, and space requirement.

In United States patent 3,480,875, R. V. Pole, has disclosed

a scanning laser device, in which the spatial orientation of the laser beam in the resonant cavity is controlled by passing through a combination of a retardation plate and a Kerr cell inside the laser cavity. At a specific angle as determined by the Kerr cell, loss is minimum for the laser beam, and therefore the laser beam will oscillate in that preferred direction.

While this method allow a scanning of large angles, the scan speed is limited by the laser build-up time, for which the laser beam intensity will be re-established at each new beam direction. Another drawback of this arrangement is the variation in the laser intensity, during the laser build-up.

In United States patent 3,432,771, W. A. Hardy, disclosed another scanning laser, in which the optical cavity consists of a focusing objective, and spherical reflectors or equivalent optics which consists of a lens and a plane mirror. The scan angle is magnified most effectively in an optical arrangement that the two end reflectors forms a nearly concentric cavity with the focusing lens at the center of focus. The drawback is the cavity is tolerant of diverging beam to build up inside the cavity as illustrated in the Fig.1 of the patent, hence that laser output has high content of multiple transverse mode. With an increase of the radius of curvature of the scan mirror and keeping its location fixed, the multi-mode content can be reduced, but the scan range with approach to that of the actual scan angle with a possibly a small magnification factor. As suggested by its preferred embodiment with an electro-optical

beam deflector, the scan angle will be only a few milli-radiant if a near diffraction-limited laser beam is to be produced.

There has not been a successful apparatus and method to overcome the above deficiencies of the prior art until the emergence of the present invention.

#### SUMMARY OF THE INVENTION

It is an object of the invention that the laser medium is to be pumped by plurality of laser beams in a longitudinal direction, such that high excitation density is achieved in the laser medium.

It is another object of this invention to disclose a construction of a high speed scanner-laser amplifier system, which has the capability of large scan angles, and emitting high quality, near diffraction limited laser beam. The scanner of the present invention can position a laser beam in two dimensional in a random access mode at high speed.

It is another object of the invention that the scanner-amplifier system generate ultra short laser pulses in 1-500 pico seconds duration at a multi-kilo Hertz repetition rate and the energy of each laser pulses is amplified in a controlled manner to a desired level up to the damage level of the optical components.

It is another object of the invention that the laser medium is to be pumped by plurality of laser beams in a longitudinal direction, such that high excitation density is achieved in the laser medium.

It is another object of the invention that the scanner-amplifier system can place an individual high energy laser pulse at a precisely intended angular location in a two dimensional space.

It is yet another object of this invention to construct a Ti:Al<sub>2</sub>O<sub>3</sub> laser with high laser pulse rate, in the range of 1000 to 50,000 pulses per second, and with high average laser power, in the range of several watts or higher.

It is a yet another object of this invention that each of this laser pulse has high peak power, and a short pulse duration, of sub-pico seconds to hundreds of pico seconds.

Still another object of this invention is to generate stable and high conversion efficiency in the second harmonic laser wavelength, which is used to generate population inversion in the Ti:Al<sub>2</sub>O<sub>3</sub> laser medium.

It is an object of this invention to propose a novel method to attain the high pump power in the second harmonic wavelength for the Ti:Al<sub>2</sub>O<sub>3</sub> laser.

The preferred method for controlling the direction of the laser beam consists of a pair of scanning mirrors driven by piezo actuators. The mirror pair are driven in tandem. The scan angles of the mirror pair are summed and amplified by an optical arrangement. Two convergent spherical lenses of un-equal focal length are arranged between the scanning mirrors in such a way that a laser beam will be travelling inside the cavity in which the boundary is defined by the scan mirrors. For each round trip



of the laser beam inside the cavity, the angle of the laser beam to an exit window increases in multiple of the actual scan angles of the scan mirrors.

In accordance with this invention, the direction of the laser beam emitted from the scanner-amplifier system is controllable in two dimensions, in high speed, and with high precision.

In a preferred embodiment, the laser beam is generated by an amplifying means with a seeding laser pulses. Optical retardation plate, Pockel cell, and polarization dependant optical elements are used for the control of a seed laser beam and directing that laser beam in the amplifier cavity. A laser gain medium is included in the cavity. Means for exciting the laser medium, and to generate multi-kilo Hertz, ultra short duration laser pulses are disclosed in the invention. Means for controlling the timing and the synchronization of the seed pulse, the pump source, and the amplified laser pulses inside the scanner-amplifier cavity are also provided.

An object in accordance with the present invention is to provide a scanner-amplifier unit which accepts a low energy laser pulse and emits an amplified laser pulse at a predetermined angular positions in two dimensions.

It is another object of the invention to provide a combiner for combining a plurality of laser beams that does not require any form of specific polarization in any of the component beams.

It is an object of such a combiner, that it can form a beam

bundle consisting of large number of beams in a small cross section.

It is yet another object of this invention to provide a novel method of combining a plurality of laser beams to provide a high power laser beam source for end pumping configuration of a laser beam.

This combiner eliminates the limitation imposed by the physical size of the beam steering optics and the optical mounts.

Earlier method of beam combining relies on the direction of the linear polarization, and this method is limited to combining two beams only.

Other advantages and features of the invention will become apparent from the following description of several embodiments thereof, shown in the attached drawings, in which:

#### BRIEF DESCRIPTION OF THE DRAWING FIGURES

Figure 1 is a schematic diagram of the integrated scanner-amplifier unit, consisting of a series of intra-cavity optical elements;

Figure 2 is a schematic diagram showing a second embodiment of the integrated scanner-amplifier unit of the invention;

Figure 3 is a schematic diagram showing the process of angular amplification for the laser beam inside the scanner-amplifier cavity;

Figure 4a is a schematic showing of a means of generating stable second harmonic laser power;

Figure 4b is a perspective showing of a spatial combiner for

combining the plurality of pump beams of Figure 4a;

Figure 4c schematically depicts the combining of the beams of Figure 4a into a single second harmonic beam from the generated beam of Figure 4a;

Figure 5a is a perspective exploded showing of a method of mounting the laser medium;

Figure 5b is a cutaway perspective showing of the laser medium of Figure 5 enclosed in a water jacket for cooling;

Figure 6 is a block diagram showing the electrical connections between the mode-locked laser driver, the timer-divider, the Pockel,s cell driver and the Q switch driver of the pump laser; and

Figure 7 is diagram showing the synchronization between the mode-locked laser pulses, the selected laser pulses after the timer-divider electric circuit, the Q switched laser pulses for pumping the gain medium and the half-wave optical switch wave form.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the preferred embodiment, a laser scanner-amplifier system 8 with Ti doped sapphire  $\text{Al}_2\text{O}_3$  is used as the laser medium. However, the laser medium can be other tunable solid state laser materials, such as alexandrite, emerald, Cr:LiCaF, Cr:LiSrF, Cr: forsterite, color center lasers, or rare earth ions laser media, such as Nd, Pr, Er, Tm, Ho, or other transition metal ions such as Co, Ni in various solid state crystal hosts, including oxides or fluorides.

A laser pulse train from a mode-locked Ti doped  $\text{Al}_2\text{O}_3$  laser 10 in Fig. 1 is to be used as a seeder to the amplifier scanner system. The laser pulse frequency of the mode-locked laser, as is well known in the art, can be controlled by the round trip time of the laser pulse inside the mode-locked laser and it is at twice of the driver frequency of the electrical signal applied to the mode locker crystal. The frequency is chosen such that time period between adjacent pulses bears a preferred relationship with the arrangements of the optical elements inside the scanner-amplifier system. In the case of Ti doped  $\text{Al}_2\text{O}_3$ , a continuous wave laser 12 having a beam 13 such as, but not limited to, an argon gas laser operating at 514.5 nm or a frequency doubled YAG or YLF lasers at 532 nm and 527 nm respectively, can be used as the pump source. The pump laser beam 13 is focused into the mode-locked laser medium with a convergent lens as designed by 14. The arrangement of a laser-pumped mode-locked laser is well known in the art and a commercial model is available from Spectra physics, Fountain View, California.

The mode-locked laser beam 15 passes through a set of beam conditioning optics, 16 and 18. In Figure 1, the beam cross section is expanded by a negative (concave) lens 16 and a positive (convex) lens 18 with their focuses coinciding to form a expansion telescope. The expansion ratio can vary between 2 to 10 by choosing the appropriate focal lengths of the elements 16 and 18 and is determined by the mode-matching requirement between the seed beam 13 and the spatial mode of the amplifier cavity.

By centering the lenses along the laser beam minimum beam distortion and good beam collimation can be achieved as the seed beam 13 exits the optical element 18.

The seed beam is directed by high reflective mirrors 20 and 22 into the amplifier cavity 23. The beam first enters the cavity through a dielectric coated mirror 24 which has the optical characteristics that a pi-polarized laser beam (with the electric field vector horizontal to the plane of incidence) has over 96% transmission, a pi-polarized laser beam (with the electric field vector vertical to the plane of incidence) has over 99% reflectability. Such thin-film polarizer elements are supplied by Burleigh NorthWest, Fishers, New York. The scanner-amplifier cavity 23 is confined between the scanner mirrors 26 and 28, both of which are highly reflective mirrors. The scanner mirrors are each mounted on a gimbal mount 29 with 90 degree tilts in both the horizontal and the vertical (x-y) directions. The design of the gimbal mount can be illustrated as a mirror mount model number MM-1 manufactured and supplied by the Newport Corporation, Fountain Valley, California, with appropriate modifications to shorten the pivot point distance and an increase in the spring force. The x-y tilts are achieved by piezo-electric actuators 31 with material such as PZT which can have a linear travel of 40 microns of full scan range at about 1000 Hertz, and at higher frequencies with smaller travel range. Such piezo-actuators are supplied by a number of suppliers, including Burleigh Instruments, Fishers, New York. The scan mirrors 26 and

28 are driven in the same direction at the same angular degree either independently or in tandem in both the x and y directions.

The operating characteristics of the piezo actuators may have small variations. The overall scan angles of the laser beam as emerged from the scanner-amplifier is to be calibrated against the voltage applied to the piezo actuators 31, taking into the account of the small amount of the hysteresis from the piezo electric effect.

A pair of concave lenses 30 and 32 are included inside the scanner-amplifier cavity. The focal lengths of the lenses 30 and 32 are such that the focal length of lens 30 is chosen to be as large as possible, yet the size of scanner-amplifier is to be practical and convenient for use, and the focal length of lens 32 will be as short as possible, yet not so short as to cause optical break down at its focal point. The relative locations of the lenses 30, 32 and end mirrors 26 and 28 are such that the mirror 26 and 28 are to be at the focal point of the lenses 30 and 32 respectively, and the separation between the lenses is to be the sum of their focal lengths. Another dielectric coated mirror 34 which has similar characteristics as mirror 24, is used as a turning mirror and also as an exit mirror where the laser beam 15, intensity amplified and scan-angle amplified, emerges from the scanner-amplifier unit 8.

Other control elements inside the cavity include a Pockel's cell 36 which is consisted of a  $\text{LiNbO}_3$  or other electro-optical crystal such as KDP. Pockel's cells are commercially available

are available from several sources, one such source is Medox Electro-optics, of Ann Arbor, Michigan. With the application of electric voltage across the electro-optical crystal, a half-wave retardation in the electric field vector of the laser beam can be generated, which turns the linear polarization of a laser beam traversing the crystal, from a horizontal polarization to vertical, and vice versa. A half-wave retardation plate 38, placed next to the Pockel's cell 36 is for adjusting the polarization of the beam before it reaches the mirror 34, so that the beam will either stay inside the cavity or to exit the cavity at mirror 34. A thin etalon 40 with partial reflection coating on both faces at the laser wavelength is for controlling the gain bandwidth of the seed beam 13. By choosing the appropriate finesse of the etalon, the wavelength width of the laser beam is reduced accordingly, compared to the seed beam bandwidth. The pulse duration is lengthened due to the reduced spectral content in the laser pulse. Hence the output laser pulse can be varied from a minimum which is that of the seed pulse, which is about 1 pico second (ps) in the case of  $\text{Ti:Al}_2\text{O}_3$  as the laser medium in the mode-locked laser, to as much as a several hundred ps. Another method for expanding the pulse duration can be achieved by stretching the pulse spatially with an optical grating, not shown. before the pulse is injected into the scanner-amplifier cavity. Such a device can be inserted in the beam path 21 as shown in Figure 1. For shorter pulses, a commercially available pulse compressor unit consisting basically of a single-mode fiber

and a grating pair, can be placed in the beam path 21 as can the grating alone hereinbefore mentioned. The compressor unit can be obtained from Spectra-Physics Lasers, Mountain View, California.

Referring now to Figure 1a, in a second embodiment, a laser gain medium 42, is located near the scanner mirror 26. A aperture cavity aperture 44 which has a fixed or adjustable iris with two translational degrees of freedom for proper centering with the fundamental laser mode location inside the cavity. The laser media is optically pumped by a laser source 48 which will be described hereinafter in more detail. The second embodiment provides enhancement of the laser beam intensity inside the scanner cavity, such that the beam intensity increases by extracting energy stored in the grain medium 42.

#### OPERATION OF THE PREFERRED EMBODIMENTS

For the purpose of illustration, an angle is being scanned in the horizontal plane (the x-plane). A scan voltage is applied to both piezo actuators 31 for positioning the gimbal mirror mounts for scan mirrors 26 and 28 in the same direction to the same degree, as an example, both pushing the mirrors forward as shown in Figure 1. A half-wave voltage electrical wave form signal is applied to the Pockel's cell, as illustrated in Figure 2b. The time sequence from 2(i) to 2(vi) marks the time development of the optical retardation of the Pockel's cell 36. A voltage is to start at time 2(ii), and the optical retardation reaches half-wave at time 2(iii). The voltage is turned off at time 2(iv), and reaches zero retardation at time 2(v). The time



duration between 2(ii) and 2(iii) is referred to as the rise time of the Pockel's cell for a half-wave retardation. The duration between 2(iv) and 2(v) is the fall time for the same. Since the seed laser pulse is in the pico second range, the spatial extent of the laser energy is localized in the range of millimeters. The cavity distance between scan mirrors 26 and 28 is, for practical purpose, in the range of tens of centimeters to tens of meters. Therefore, for all practical purpose, the laser pulse can be considered localized and is represented by markers 2(i) to 2(vi) as it travels through the scanner-amplifier cavity. The seed laser beam, at time 2 (i) travels towards the scanner-amplifier cavity, and enters through the thin film polarizer mirror 24. As illustrated in Figure 2a, the beam 15 has a linear polarization with the electric field vector in the horizontal direction, as indicated by the arrow. The beam passes through the lens 30, and is focused at a point before lens 32 which collimates the beam due to the confocal arrangement of the lenses set 30 and 32. The Pockel's cell (PC) voltage is at the zero level, and the polarization of the seed beam is not changed. The Pockel's cell voltage turns on at time 2(ii), right after the laser pulse exits the PC crystal. The polarization changes by 90 degrees after passing through the half-wave plate 38, and is now vertical, as indicated by a small circle on the beam path. The beam is then reflected by the thin film polarizer mirror 34 directing the beam towards the scan mirror 28.

In Figure 3, the beam path and the angle of incidence at

mirrors 26 and 28 are illustrated. Assume that a voltage  $V_1$  is applied to the piezo actuator 31, which induces a scan angle of  $\theta_1$  from its zero degree incidence, at which the mirror is at the normal incidence with the incoming seed beam. The reflected beam is at an angle, 2 times  $\theta_1$  from the incoming beam. The vertical polarization of the beam changes by 90 degrees after passing through the half-wave plate 38. The PC voltage reaches half-wave retardation at 2 (iii), see Figure 2b, before the laser pulse reaches the PC. On passing the PC, the polarization is rotated 90 degrees and is now vertical. The lens 30 recollimates the laser beam 15 and the thin film polarizer 24 is now at high reflection with the vertically polarized beam. The beam 15 then travels towards the laser gain medium 42 and the cavity aperture 44. Assuming that a voltage  $V_2$  is applied to the actuator 31 in the mirror gimble mount 29 for the scan mirror 26, and an angle rotation of  $\theta_2$  from the normal incidence is resulted in the x-plane, where the normal incidence is defined as the scan mirror angular position for both 26 and 28 at which the seed laser beam 2(i) will retrace its beam path after reflection from both these mirrors. The reflected beam is therefore, at a larger angle than the incident angle before impinging on the mirror 26, by an angle, 2 times  $\theta_2$ , as shown in Fig. 3. For ease of explanation, the following discussion is directed to ejecting the laser beam after only one reflection from each of the mirrors 26 and 28; However it should be understood that it is contemplated that a plurality of reflections from each mirror

within the device prior to the beam exiting therefrom. By so choosing, the PC voltage turn-off starts after the beam emerges from the PC at time 2(iv), and the retardation is zero at 2(v) before the beam reaches the PC on its return trip from the scan mirror 26. The vertical polarization remains vertical after passing the PC, and is rotated to horizontal after the half-wave plate 38. The thin film polarized mirror is now transmissive for the laser beam, and the laser beam emerges from the amplifier-scanner of the invention with a scan angle, resulting from the sum of the effects of the scan angles  $\theta_1$  and  $\theta_2$  from the scan mirrors 28 and 26 respectively.

It should be understood that invention makes use of the scan mirrors 26 and 28 repeatedly from one or more round trips of the beam inside the cavity to amplify and precisely direct the beam angle before exiting mirror 34.

In our preferred embodiment, the PC voltage turn-off, at times 2(iv)-2(v), is to be applied at the last leg after one or more round trips between the two scan mirrors 26 and 28. In the case where the voltage turn-off is postponed, as in the illustration in Fig. 2(a), the polarization of the reflected beam from mirror 26 is rotated to horizontal after the PC, which is still at its half-wave voltage, and back to be vertical again after the half-wave plate 38. Therefore, the mirror 34 is highly reflective. The beam is trapped inside the cavity, and the beam angle increases with each reflection with either of the scan mirrors.

Further, in addition to changing the beam angle, the optical arrangement enhances the overall scan angle of the beam with a power multiplying enhancement factor.

If the focal length of the lens 30 is longer than that of lens 32, by a factor,  $M$ ,

$$M = f_{(30)} / f_{(32)},$$

where  $f_{(30)}$ ,  $f_{(32)}$  are the focal lengths of the lenses 30 and 32 respectively. The angle of incidence on mirror 28 is  $\theta_1$ , and the angle of incidence on mirror 26 is

$$\theta_1 / M + \theta_2.$$

Notice the angle reduction of the  $\theta_1$  due to the difference in the focal length of the lenses.

On passing through the lenses system from 30 to 32, the reverse, i.e. a magnification of the effective angle, occurs. The incident angle on mirror 28 is now

$$(\theta_1 / M + \theta_2) * M \theta_1.$$

In the illustration in Fig. 2(a), in which the laser beam is to exit the cavity after one reflection from mirrors 26 and 28, the output beam would have a scan angle of

$$2 * (\theta_1 / M + M * \theta_2).$$

Notice that the scan angle due to mirror 26,  $\theta_2$ , is magnified by a factor  $M$ .

If a total of  $N$  reflections are allowed to occur for each of the two scan mirrors, the final scan angle of the exit beam is

$$2N * (\theta_1 / M + M * \theta_2).$$

Since each reflection or transmission on an optical surface causes a certain amount of intensity loss and optical distortion in the laser beam, ideally the intended scan angle will be achieved with the smallest number of optical surface contacts. If the scan mirrors have identical gimble mounts 29 and piezo actuators 31, the mirrors can be scanned in tandem, and  $\theta_1$  and  $\theta_2$  will be substantially equal. The optical loss due to scattering from all the optical elements inside the cavity is reduced by the factor

$$(Mt_1)/2.$$

For  $M=3$ , and 10 round trip inside the cavity, the scan angle is amplified by 20 times more than the amplification of the scan angles from two like but uncoupled piezo mirrors.

It is also clear that all the fore-going discussion about scanning in the horizontal direction, is also applicable to the vertical direction (a Y-scan), by applying the scan voltage to the piezo actuator which controls the vertical tilt of the scan mirror. By applying the appropriate voltages to the actuators controlling the horizontal and the vertical scan directions, the laser beam can be directed to any predetermined location in the two dimensional angular space.

The pump source 48 of the  $\text{Ti: Al}_2\text{O}_3$  in the amplifier cavity in Fig. 1 consists of two major components, namely, a Nd doped YAG or YLF laser which is continuously pumped by arc lamps such as Kr or Ar gas lamp, which is supplied by ILC Technology, Sunnyville, California, or by semiconductor diode arrays with the

emission laser wavelength to match the absorption band of Nd doped YAG or YLF. Several hundred to over one thousand watts of continuous wave laser output power from Nd: YAG is attainable with multiple lamp-pumped laser heads inside a laser cavity. Such laser is supplied by Lasermetric, Orlando, Florida, and a number of other industrial YAG laser suppliers.

In a preferred embodiment, the Ti ion has an absorption band centered at about 520 nm, with a full width at half maximum of about 100 nm. The second harmonic wavelengths of the Nd doped YAG and YLF are centered around 532 nm and 527 nm respectively, and both are usable as a pump source.

In the second harmonic generation (SHG) process, one of limiting factor in the conversion efficiency and the power stability is the temperature gradient induced by absorption of the laser at its fundamental and second harmonic frequency. Choosing a second harmonic crystal with good thermal conductivity, and cooling the crystal by liquid flow or by contact cooling are among the common methods to extend the upper limit of the input fundamental laser power to the SHG crystal.

Referring now to drawing Figures 4a, 4b and 4c, the output laser beam 55 of a high power, acoustic-optical switched, Nd doped YAG or YLF laser beam source 56 is directed to a series of partially reflecting beam splitters 57, which are coated with dielectric so that, at the 45 degrees incidence, they all have high transmission for the second harmonic wavelength, and each succeeding splitter is a highly reflective at the fundamental

wavelength of the laser source 56, so that the laser beam power is to distribute equally among each branch when they are directed towards the SHG crystals 60. The crystal 60 is chosen for high nonlinear coefficient, good acceptance angle, and high tolerance on temperature gradient. KTP, is among the top choice as a SHG crystal for conversion at 1.04 to 1.06 microns.

In a preferred embodiment, 20-60 watts of average power will be achieved in the beams 1-5 of Fig. 4a. To further increase the conversion efficiency, a convex lens 58 can be inserted between each splitter 57 and each SHG crystal 60, such that the crystal is at the focal distance,  $f_{(58)}$  from the lens, where the beam cross section is the smallest and the laser power density is the highest. The focal length of the lens is chosen to optimize for the acceptance angle of the SHG crystal. A spherical concave mirror 62 is highly reflective at both the fundamental and the second harmonic wavelength is placed at the radius of curvature of the mirror 62,  $R_{(62)}$  from the first surface of the crystal, where the laser beam enters the crystal. This optical arrangement allows for the return beams of both the fundamental and the second harmonic, to retrace the beam path of their first passage in the crystal, and ensure a good beam overlapping in the crystal even there may be walk-off between the beams after their first pass.

To illustrate our embodiment, we combine five beams at the second harmonic wavelength with a novel spatial combiner 64. As shown in Fig. 4(b), the combiner 64 is a six face optical element

which has four sides 63a, 63b, 63c and 63d, each of which form a 45 degrees with the base face, and a top face 65 which is parallel to its bottom face 67. The side faces are coated for high reflectivity at 45 degrees at the second harmonic wavelength, and the top and bottom faces are coated with anti-reflection coating at the second harmonic wavelength. As shown in Fig. 4c, by using beam steering optics, the five beam from Fig. 4a can be reflected off the side faces of the combiner 64, and one beam (beam 2 in Fig. 4c) can transmit through the parallel faces. The beams are adjusted such that they re-collimated and are parallel with each other. A convex lens 66 is centered symmetrically in the beam path, and focuses the five beams into a common focal point. This optical element 66 can be a replacement or an equivalent to the element 46 of Fig. 1.

It also follows from the present invention that additional beams can be combined with a spatial combiner with additional facets on the combiner. As an example, a hexagon instead of a square top, can combine up to 7 beams.

In another embodiment, the facets can be formed on more than one layer, such as 4 facets on the top tier and 6 facets on the second tier.

In all end pumping configurations, the pump beam is absorbed by the laser active ions in the crystal host. The energy distribution in the laser medium is a negative exponential function, with a maximum at the entrant face. For efficient cooling, and to minimize the distortion of the laser beam, the



laser medium in the invention is to be in a cylindrical laser rod form. Conventional laser rod is mounted with the end faces outside of the contact with the coolant. In fig. 5a, the preferred embodiment consists of a Ti:Al<sub>2</sub>O<sub>3</sub> laser rod with a recessed collar 50. A thin wall tube made of undoped sapphire 52 is to fit at the end sections of the laser rod. The tube piece is glued to the laser rod, and the whole has a cylindrical shape as shown in Fig. 5(b). This cylindrical piece is then mounted to a liquid cooled envelope similar to the ones used in an arc lamp pumped laser. A water flow channel around the laser medium and the extension is shown in Fig. 5(b), in which the water inlets and outlets are shown schematically. O-rings 54 are retained in such a manner that the coolant is sealed from coming into contact with the flat laser surfaces of the laser rods. The tube extension allow the whole laser medium to be in contact with the liquid coolant. Using the same material in the extension tube also minimize stress as a result of difference in thermal expansion coefficient, with temperature variation in the whole assembly.

In another embodiment, an additional pump source can be applied through mirror 24 collinear with laser path from pump source 48, such that the laser media is pumped from both ends. In another embodiment, additional laser media is to be included in front of the scan mirror 28, and a pump configuration identical to optical elements 46 and 48, pumping one end of the laser medium, or pumping from both ends of the laser medium, is

to be applied to the laser medium near mirror 28.

Multi-kilo Hertz laser operation is achieved with the following method. A synchronized electrical wave form is tapped from the mode locker driver 66. According to the desired repetition rate, the synchronized signal can be divided electrically by a timer divider circuit 68, as shown diagrammatically in Figure 6. The resultant frequency output of the timer-divider determines the laser frequency of the scanner-amplifier system. The output electrical signal of the divider box is then time-delayed through delay generators 70,74, commercially available from Stanford Research Systems, Sunnyville, California. One of the delayed signals 71 is fed into the Q-switched driver 72 in the pump laser 48, and a second time-delayed signal 75 is fed into the Pockel's cell driver 76.

The timing of the electrical signals and the laser events are illustrated in Fig. 7. In the top trace 7(a) of Fig. 7, multi-mega Hz (30-200 Mhz) mode locked laser pulses are represented by equally spaced laser spikes at time interval equal to twice the mode locker driver frequency. After the timer-divider circuit, electrical signals at multi-kilo hertz Hz (1,000-50,000) is generated at the output of the timer-divider box, as represented by the trace 7(b). At a time delay  $T_1$ , the Q-switch driver for the pump laser is turned on, in trace 7(c), generating a short pulse of the second harmonic laser pump pulse at a time delay  $T_p$ , corresponding to the build up of the pump pulse, a characteristic of the pump configuration and the gain

factor at the pump laser medium. The second harmonic pump pulse is absorbed in the  $\text{Ti:Al}_2\text{O}_3$  laser medium, in trace 7(d). The Pockel's cell is switched on at a time delay  $T_2$  relative to a synchronized timer-divider signal, which is the pulse after the one that triggers the Q-switch driver. the time delay  $T_2$  is determined by the actual location of the seed laser pulse from the mode locked laser, as afore mentioned along with the discussion of Fig. 2a. The delay time  $T_1$  is to be adjusted so that the peak of the population inversion is to occur when the Pockel's cell crystal reaches the half-wave retardation point of  $2(\text{iii})$  as shown in fig. 2b.

Other variations, ramifications and applications of this invention will occur to those skilled in the art upon reading the present disclosure. These are intended to be included within the scope of this invention or defined in the appended claims.

What is claimed is:

1. A laser scanner-amplifier comprising:  
a first source of producing a first laser beam and  
an optical cavity through which said laser beam passes,  
comprising:

light control means for introducing the said laser beam  
into said cavity and circulating said laser beam inside said  
cavity and ejecting said laser beam out of said cavity all in  
predetermined time sequence;

means for directing said laser beam while circulating  
inside said cavity; and

means for the control of the direction of said laser beam  
at the beam exit from said cavity.

2. The invention as defined in claim 1 additional  
comprises means for laser beam intensity amplification while  
circulating within said cavity.

3. The invention as defined in claim 1 wherein said  
laser beam emerges from said cavity with said laser beam  
directed at a selected angular position in a two dimensional  
space.

4. The invention as defined in claim 1 wherein said  
laser beam consists of laser pulses which have pulse duration  
ranging from 10 femtoseconds to 10 nanoseconds.

5. The invention as defined in claim 1 wherein said  
laser beam is from a mode-locked laser.

6. The invention as defined in claim 1 wherein the cross  
section of said laser beam is variable, and said cross-section  
is preferably at its substantially largest allowable dimension.

7. The invention as defined in claim 1 wherein said  
light control means is a Pockel's cell and a first pair of  
fixedly positioned mirrors are coated with metallic or  
dielectric material, at least one of which is transparent to a  
first polarization of said laser light beam directed upon, and  
substantially reflective to a second polarization of said laser  
light beam directed upon.

8. The invention as defined in claim 7 wherein said

first and second polarizations are mutually orthogonal to each other, representing the two eigen states of a linearly polarized light.

9. The invention as defined in claim 1 wherein said means for controlling said laser beam direction comprises:

a pair of positionable mirrors located within said optical cavity; and

a pair of convex lenses of unequal focal length positioned within said cavity, the positions of which are such that the lenses are separate by a distance substantially the sum of the focal lengths, and each of said pair of positionable mirrors is at the focal point of one of said lenses, and the lens with a longer focal length is nearer to one of the first said mirror pair, upon which the first said laser beam enters said cavity.

10. The invention as defined in claim 9 further comprises piezo electrical elements wherein said positional mirrors are each mounted on a gimble mount which is connected to a piezo electrical element and said gimbles are positionable through X and Y axis by means of applying a voltage potential to said piezo electric elements.

11. The invention as defined in claim 10 wherein said positionable mirrors are independently positionable.

12. The invention as defined in claim 10 wherein said positionable mirrors are positioned in tandem in both X and both Y axis.

13. The invention as defined in claim 10 wherein said positionable mirrors are each positionable to substantially the same X, Y coordinates.

14. The invention as defined in claim 1 wherein said means for controlling the direction of said laser beam comprises: at least two positionable mirrors and

at least two convex lenses of unequal focal length, the positions of each of said lens inside said optical cavity are such that the lenses are separate by a distance about the sum of the focal lengths and each of said positionable mirrors is at the focal point of one of said lenses, and the lens with the

longest local length is nearer to one of the first said mirrors, upon which the said laser beam first enters said cavity.

15. The invention as defined in claim 1 wherein further comprising a pair of positionable mirrors, said means for circulating said laser beam inside said cavity comprises a pair of convex lenses, the positions of which are such that the lenses are separate by a distance about the sum of the focal lengths and each of said pair of positionable mirrors is at the focal point of one of said lenses, such that said laser beam circulates between said positional mirrors.

16. The invention as defined in claim 1 additionally comprising a pair of positionable mirrors, said means for circulating said laser beam inside said cavity comprises a pair of convex lenses, the positions of which are such that the lenses are separate by a distance about the sum of the focal lengths, and each of said second pair of positionable mirrors is at the focal point of one of said lenses, such that said laser beam is collimated at said positionable mirrors.

17. The invention as defined in claim 2 wherein said means for the intensity amplification of said laser beam comprises:

- a laser gain medium and
- an optical pump source, directing its optical energy at said laser gain medium.

18. The invention as defined in claim 17 wherein the spectral band of the gain region of said laser medium has a substantial overlap with the wavelength of said first laser beam.

19. The invention as defined in claim 17 wherein said optical pump is either a continuous wave light source having a broadband emission spectrum, covering one or more optical pump bands of said laser gain medium.

20. The invention as defined in claim 17 wherein said optical pump source is a repetitively pulsed wave light source having a broadband emission spectrum, covering one or more optical pump bands of said laser gain medium.

21. The invention as defined in claim 20 wherein said optical pump source is a second laser beam being directed longitudinally in said laser medium along the direction of said first laser beam, and overlaps substantially said first laser beam.

22. The invention as defined in claim 17 wherein the laser wavelength of said laser medium is tunable over a spectral range.

23. The invention as defined in claim 17 wherein said laser medium consists of an element of transition metal selected from the class including Ti, Cr, Co, V, or Mn as the active lasing element.

24. The invention as defined in claim 17 wherein said laser medium consists of one or more or color centers as the active lasing element.

25. The invention as defined in claim 17 wherein said laser medium consists of elements of the rare earths selected from the class including Ce, Pr, Nd, Ho, Tm, Er, or Yb as the active lasing elements.

26. The invention as defined in claim 17 wherein said laser medium consists of combinations of said active lasing elements selected from the class including Ce, Pr, Nd, Ho, Tm, Er, or Yb as the active lasing elements.

27. The invention as defined in claim 17 wherein said laser medium is a solid state crystal which is preferably an oxide or a fluoride crystal.

28. A method of generating a high power laser beam and controlling said laser beam in predetermined angles in two dimensional space which comprises of the steps of:

producing a first source of a first laser beam;

injecting said laser beam into a cavity of a control device comprising of means for directional control and amplifying the intensity of said laser beam;

circulating said laser beam inside said cavity of said control device; and

exiting said laser beam out of the cavity of said control device when said laser beam attains a predetermined intensity

and is at a predetermined angular exit direction.

29. The method of claim 28 additionally amplifying the intensity and angular direction of said laser beam in said control device.

30. A method of generating a high power laser beam and controlling said laser beam in predetermined angles in two dimensional space as recited in claim 26 further comprising the step of selecting part or all of the laser pulses from said first source, such that the laser pulse repetition rate is a fraction of, or the same as, that of said first laser source.

31. A method of generating a high power laser beam and controlling said laser beam in predetermined angles in two dimensional space as recited in claim 26 further comprising the step of synchronization between said injected pulse, the timing of said control means to recirculate said laser pulse, and the timing of said intensity amplification means, such that said injected laser pulse is trapped inside said cavity of said control device, and the intensity of said laser beam is amplified as said laser beam travels each round trip inside said cavity.

32. A laser scanner-amplifier comprising:

a first source for producing a first laser beam;

a first pair of fixedly positioned opposing dielectric mirrors, at least one of which is transparent and substantially non-reflective to a first polarization of said laser light beam directed thereon;

a laser light beam polarization means positioned between said first pair of mirrors, said laser light beam passing through said polarization means changes directional beam polarization from a first polarization direction to a second polarization direction, said first pair of mirrors become reflective to said second polarization of said laser beam; and

a second pair of positionable mirrors;

said laser beam is reflected and travels back and forth between said first and second pairs of mirrors through said polarization means a selected number of times prior to changing



the polarization of said laser beam by said polarization means from said second polarization direction to said first polarization direction, said laser beam exits said laser scanner-amplifier at a selected exit angle, said exit angle dependent upon the various different angular positioning of said second pair of mirrors during the back and forth travel of said laser beam between said pairs of mirrors.

33. The invention as defined in claim 32 further comprising a second source for producing a second laser beam, said second laser beam is at said first polarization direction passes through a selected one of said second pair of positional mirrors and increases the level of power of said first laser beam each time said first laser beam strikes a said selected one of said second pair of positionable mirrors whereby the power of said laser beam exiting said laser scanner-amplifier is increased each time it travels back and forth between said pairs of mirrors.

34. The invention as defined in claim 32 wherein said laser is a mode locked CW laser.

35. The invention as defined in claim 32 wherein said polarization means is a Pockel's cell.

36. The invention as defined in claim 32 wherein each of said positionable mirrors are mounted on a gimble mount positionable through X and Y axis by means of a piezo electric element.

37. The invention as defined in claim 36 wherein said positionable mirrors are independently positional.

38. The invention as defined in claim 36 wherein said positionable mirrors are positioned in tandem.

39. The invention as defined in claim 36 wherein said positional to substantially the same X, Y coordinates.

40. A laser beam frequency doubling device comprising;  
a source producing a first laser beam of a predetermined frequency;

a plurality of beam splitters;

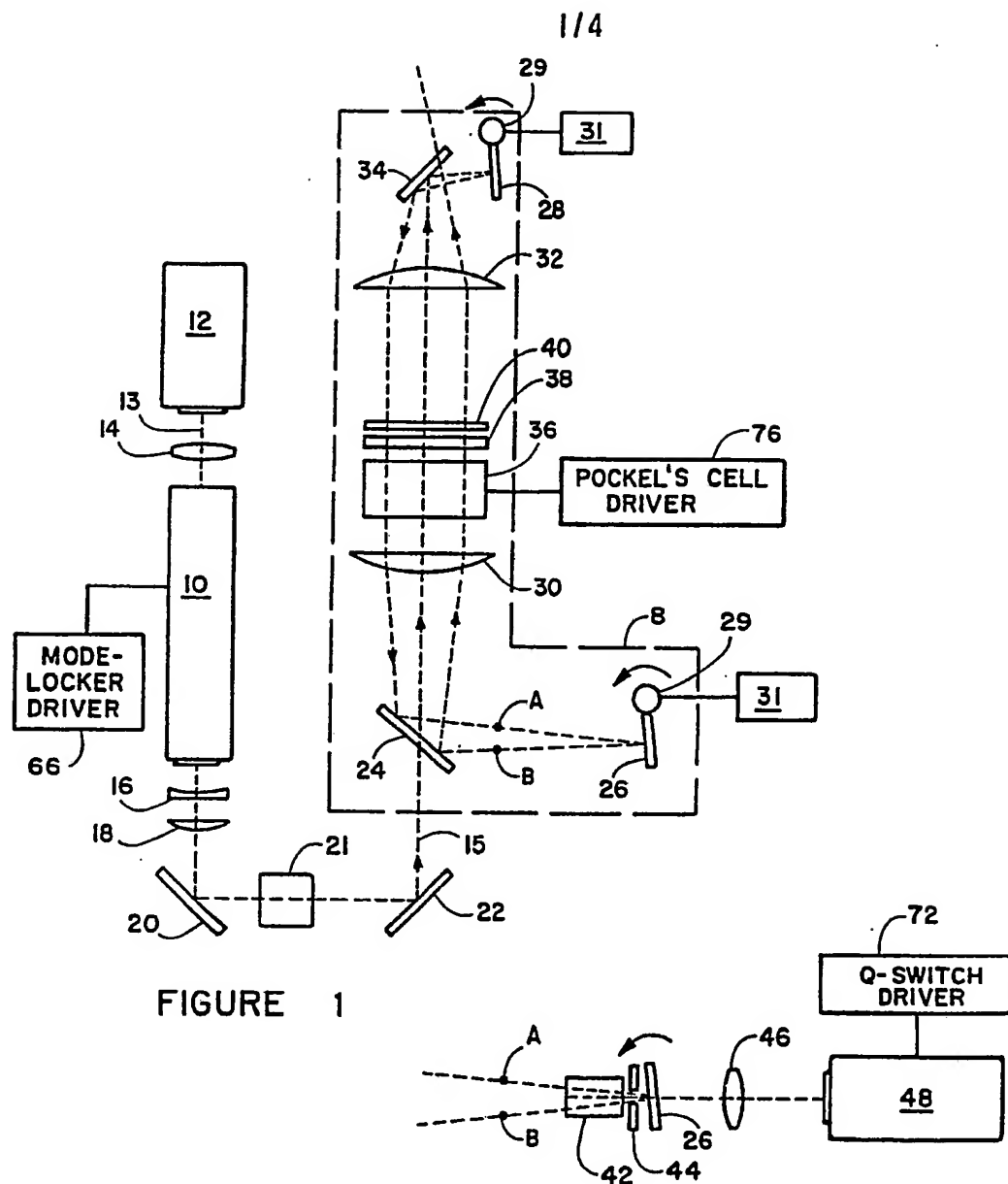
a plurality of reflector means equal in number to

**SUBSTITUTE SHEET**

said beam splitters for reflecting the split beams from said beam splitters back through their respective splitters whereby the split laser beams exit their respective splitters as separate beams of the second harmonic of the frequency of said first laser beam.

41. The invention as defined in claim 40 additionally comprising combining means for combining said plurality of split laser beams into a second laser beam having twice the frequency of said first laser beam.

42. The invention as defined in claim 41 wherein said combining means comprises a plurality of surfaces for receiving separately each of said split laser beams which exits therefrom and through a converging lens and exit said lens as a said second laser beam.



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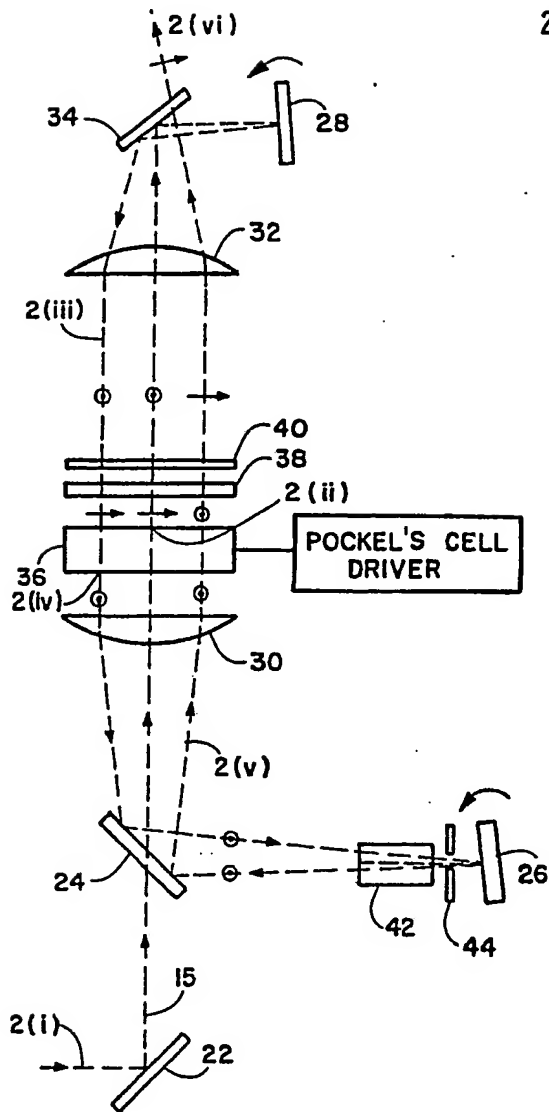


FIGURE 2 (a)

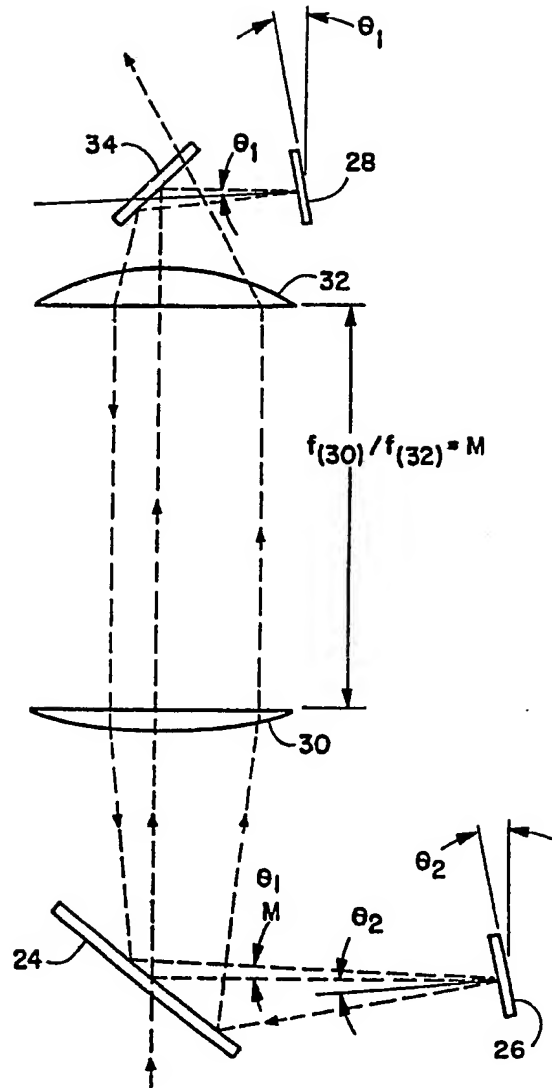


FIGURE 3

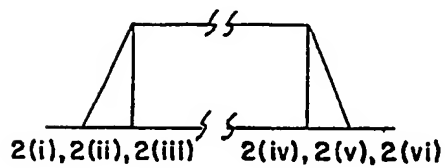


FIGURE 2 (b)

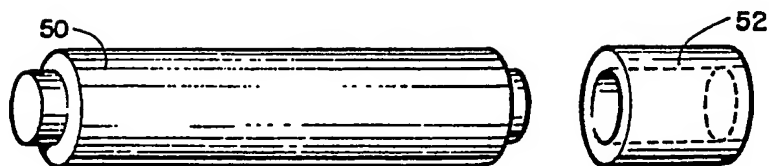


FIGURE 5(a)

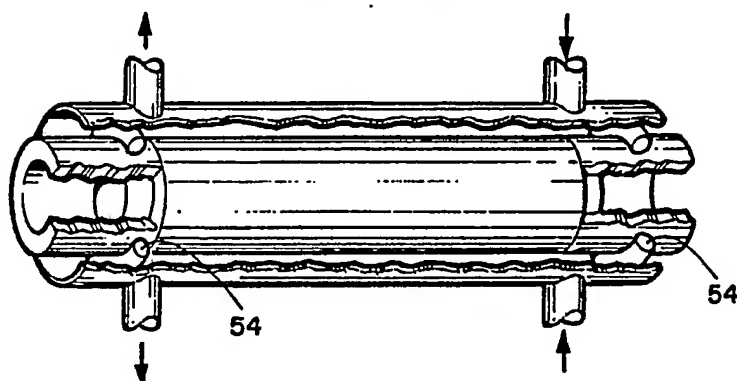


FIGURE 5(b)

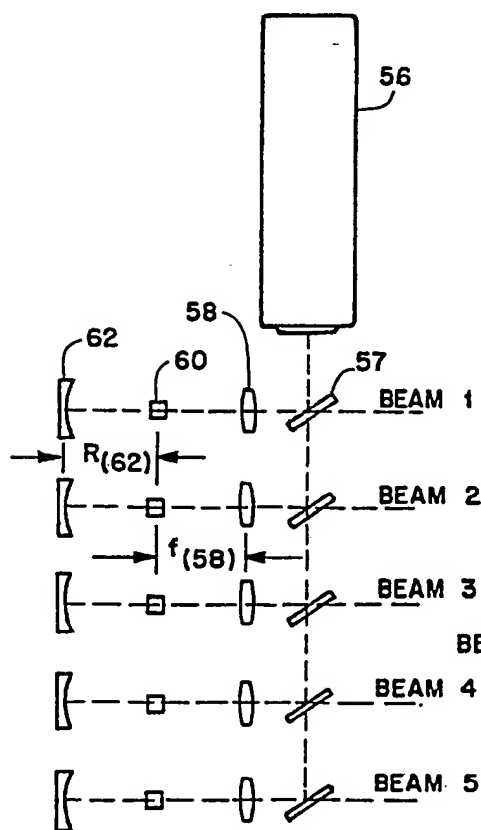


FIGURE 4(a)

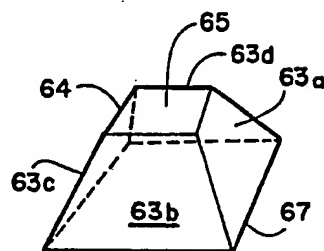


FIGURE 4(b)

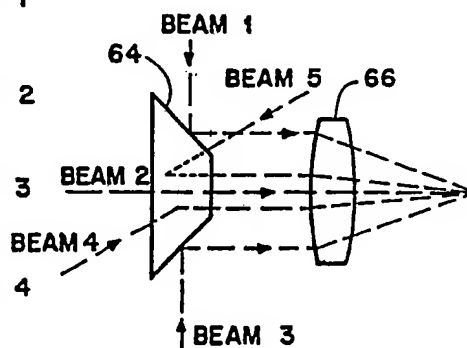


FIGURE 4(c)

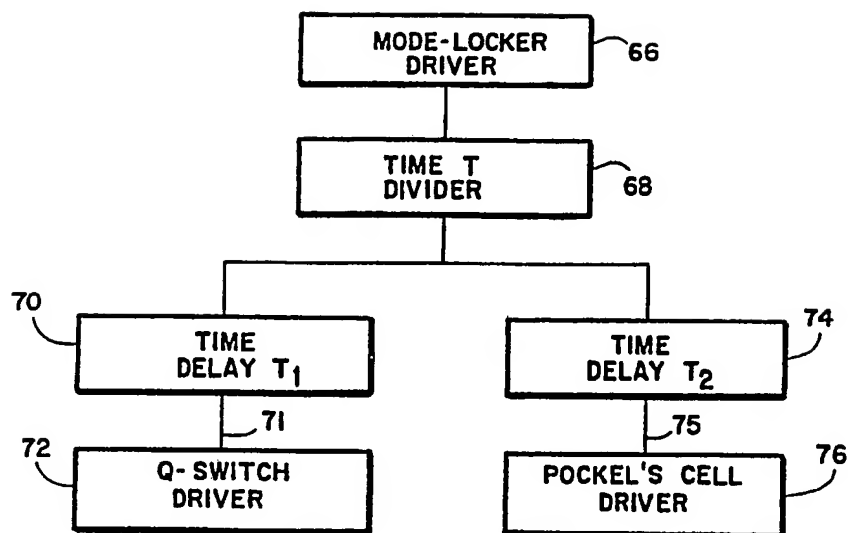


FIGURE 6

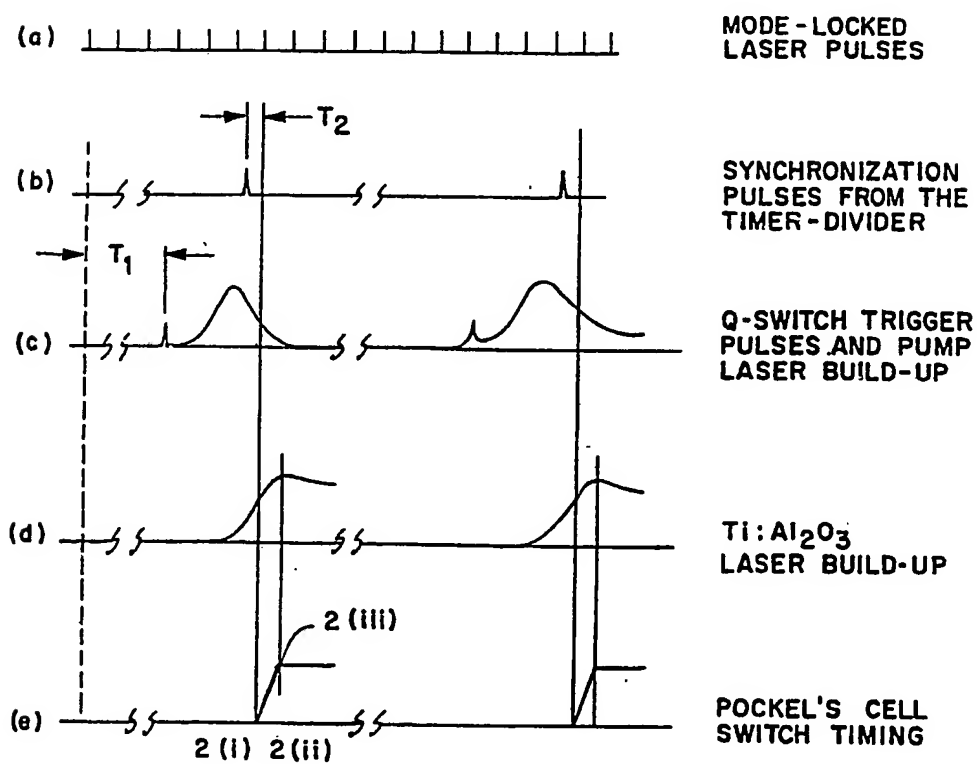


FIGURE 7

SUBSTITUTE SHEET

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US92/06487

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(5) :H01S 3/08; G02F 1/37

US CL :359/347,328

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/326; 345,346,629,634,638,639,640; 372/24,92

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,918,395 (DIFONZO ET AL.) 17 April 1990, col. 5, line 1 to col. 6, line 41 and fig. 4.	1-6,17
A,P	US, A, 5,048,946 (SKLAR ET AL.) 17 September 1991, fig. 1 and col. 5, line 11 to line 28.	37
A	US, A, 1,645,417 (COX) 11 October 1927, fig. 5.	38,39

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be part of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

21 OCTOBER 1992

Date of mailing of the international search report

20 NOV 1992

Name and mailing address of the ISA/  
Commissioner of Patents and Trademarks  
Box PCT  
Washington, D.C. 20231

Authorized officer

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Facsimile No. NOT APPLICABLE

Telephone No. (703) 308-4847

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US92/06487

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2. ☐ Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:  
Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
  
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.  
☐ No protest accompanied the payment of additional search fees.



# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US92/06487

## BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING

This ISA found multiple inventions as follows:

Group I, claims 1-36 drawn to a combination, classified in class 359, subclass 347.

Group II, claims 37-39 drawn to a subcombination, classified in claims 359, subclass 328.

Inventions I and II are related as combination and subcombination. Inventions in this relationship are distinct if it can be shown that (1) the combination as claimed does not require the particulars of the subcombination as claimed for patentability, and (2) that the subcombination has utility by itself or in other combinations. (M.P.E.P. § 806.05(C)). In the instant case, the combination as claimed does not require the particulars of the subcombination as claimed because since claims to both the subcombinations and combination are presented, the omission of details of the claimed subcombinations of Group II in the combination claims of Group I is evidence that the patentability of the combination does not rely on the details of the specific subcombination. The subcombination has separate utility such as in a system which does not include scanning.